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The research that was supported by AFOSR Grant 80-0076 was divided into three areas: 1. Anomalous dc resistivity; 2. Turbulent plasma heating due to double layers; and 3. X-ray production from a very high power z-pinch. The accomplishments in each area are reviewed in the following sections. The publications on the work supported by this grant are listed in Section 5.

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I. INTRODUCTION

The research that was supported by AFOSR Contract 80-0076 was divided into three areas:

1. Anomalous dc resistivity.
2. Turbulent plasma heating due to double layers.
3. X-ray production from a very high power z-pinch.

The accomplishments in each area are reviewed in the following sections. The publications on the work supported by this contract are listed in Section 5.

II. ANOMALOUS DC RESISTIVITY

A. Introduction

In laser heated plasmas, laser heated electrons leave the critical surface (where the laser frequency equals the plasma frequency). A return current of thermal electrons is driven toward the critical surface so that charge neutrality is maintained. In a relativistic electron beam heated plasma, the return current is driven by the requirement for current neutralization. In very high power z-pinches the current is driven by the external electric field. In all these systems, if the current of thermal electrons is high enough, then ion acoustic waves grow in the plasma. The threshold electron drift velocity is somewhat[1] larger than the sound speed if $zT_e/T_i \gg 1$, where z is the charge state of the ions, T_e is the electron temperature, and T_i is the ion temperature. Theory[2] and particle simulation calculations[3,4,5] indicate that anomalous dc resistivity develops if the electron drift velocity exceeds a threshold.

A complicating feature is that electric fields on the order of the runaway[6] electric field can be generated by the anomalous resistance. The runaway electric field is that field which doubles the electron velocity in a mean electron-ion collision time. Since the collision cross-section decreases as $1/E_e^2$, where E_e is the electron energy, the electrons just never make another collision and runaway, i.e., they are freely accelerated by the electric field. Even for fields somewhat below the runaway field, a fraction of the electrons runaway[6]. Notice that the ion acoustic waves which are responsible for the anomalous resistivity could scatter some of these freely accelerated electrons and decrease the number of runaway electrons. However, it has been shown theoretically[7] that the ion acoustic turbulence has the effect of increasing the collision cross section, but leaving the $1/E_e^2$ energy variation. Thus, the runaway field is decreased, but runaway can still occur. The fraction of electrons that runaway in a given field <u>below</u> the runaway value has been calculated based on a Fokker-Planck model for collisions[8]. Experiments on the runaway fraction have given only rough values, but they are more than an order of magnitude less than the theoretical predictions[8].

Simulation calculations of anomalous resistivity have been performed[3,4,5]. The most extensive set of calculations have been obtained by Biskamp, et al[4]. They reported two- and three-dimensional particle simulation calculations. They found a significant population of runaway electrons in addition to a strong anomalous resistivity.

We have recently[5] suggested a new mechanism for anomalous dc resistivity. Based on one- and two-dimensional particle simulation calculations, if the electron drift velocity is larger than the electron thermal velocity, i.e., $v_e > v_e$, the unstable ion acoustic waves are themselves unstable to a modulational instability so that instead of obtaining homogeneous ion acoustic turbulence, a series of highly localized, huge ($\delta n_i/n_i \lesssim 1$) wave sites are obtained. Very large ($\Delta\phi \gtrsim 3kT_e$) plasma potential jumps (double layers[9]) exist at the localized wave sites. The external field is essentially shielded out of the plasma and appears in the double layer. We find little evidence of runaway electrons. This is to be expected, because all electrons are accelerated through the localized potential and then interact with the thermal electrons on the high potential side of the site via a two stream instability. It is this interaction which gives the anomalous dc resistivity. We find larger values of anomalous dc resistivity than obtained from previous particle simulation calculations.

How do these predictions agree with experimental results? There is an extensive literature of predictions from theory and particle simulation calculations. There is also an extensive literature of experimental results[10,11]. However, there is a general lack of quantitative agreement. The main problem is that very detailed measurements need to be made to compare to the predictions. In most cases, only the resistivity has been measured. The required measurements are: energy distribution function for the electrons and ions as a function of space; and wave spectra as a function of space and angle of propagation relative to the direction of the electron drift.

B. Results

We have made detailed measurements[11] of anomalous dc resistivity in a double plasma device. High density plasma is created in a large diameter (24") cylindrical chamber. Two high transparency screens separate this chamber from a small diameter (6") cylindrical chamber in which a low density plasma is formed. The large diameter chamber is biased so that a low energy electron beam is injected into the small diameter chamber. The density of the electron beam is comparable to the plasma density in the small diameter chamber. The cylindrical walls of the small chamber are biased to reflect electrons. Thus, all electrons in the small chamber must travel to the anode which is at the end opposite to the screens. Thus, the electrons in the small chamber are drifting with an energy of about the beam injection energy. We find that a virtual cathode is created close to the screens in the small diameter chamber. Thus, an electric field is applied to the plasma between the virtual cathode and the anode. We find[11] that, under certain conditions, large amplitude ($\delta n/n \lesssim 15\%$) ion acoustic waves are excited, and a strong anomalous resistivity develops. The resistivity agrees fairly well with the theoretical predictions of Sagdeev[12]. In addition, the wave spectrum is close to predictions[13] based on this theory. Thus, these measurements have verified some important aspects of the theoretical predictions. However, we find that anomalous resistivity only occurs for a narrow range of values of the applied electric field. The problem is apparently that space charge limited flow limits the amount of current that can flow through the virtual cathode. The net result is that most of the applied electric field falls in the sheath region outside the plasma except for very special conditions.

We have constructed[14] and are now testing a second device (STING) to be used to make measurements over a large range of plasma currents and plasma densities. The STING vacuum chamber is a cylinder (diameter = 60 cm and length = 100 cm). A cylindrical tube (diameter = 8 cm and legnth = 30 cm) is aligned along the axis in the middle of the chamber. Plasma is created outside the tube. STING can be operated in one of two modes. In the first mode, plasma is only created at one end and a washer-shaped collar is placed at the entrance of the small tube so plasma is confined to only one end of the vacuum chamber. The anode is placed at the opposite end of the tube, and the tube is biased to reflect electrons. The point is that all electrons created in the large diameter chamber must transverse the tube. Thus, by adjusting the anode voltage and plasma density, a variable current can be driven in the plasma in the tube. Preliminary results indicate that large amplitude ion waves are excited in the tube. A transformer is used to apply an electromagnetic electric field to the plasma in the other mode of operation of STING. The transformer cores are ferrite toruses which are concentric with the axis of the tube. The plasma in the tube is the secondary of the transformer. In this way, we can apply very large electric fields ($E/E_R \lesssim 6 \times 10^4$).

Movable electrostatic energy analyzers will be used to measure the spatial variation of the ion and electron energy distribution functions. Probes will be used to measure the wave spectra as a function of space and angle and electron drift velocity. The experiment is controlled by a minicomputer which acquires and analyzes the data.

III. DOUBLE LAYERS

A. Introduction

A current-carrying plasma is subject to a number of instabilities. Also, strong anomalous resistivity is a universal feature of current-carrying plasmas if the current is high enough[10]. It is generally believed that ion waves[2] are responsible for this anomalous resistivity. However, there is another possible explanation involving the creation of double layers, as first suggested by Lutsenko, et al[15]. Lutsenko, et al[16], performed a set of experiments on a low density ($n \approx 10^{12}$ to 10^{13} cm^{-3}), cold ($T_e \approx 3eV$), magnetically confined, fully ionized, linear plasma. A 20 kV capacitor was suddenly connected to the anode and the cathode. The current began to flow as expected, but immediately the current was disrupted. The current remained low for a long period ($\approx$ 10 μsec) and then started to flow again. Notice that during the time the current was disrupted, the resistance of the plasma was very high, so that an observer with only the current and voltage would have stated that the plasma was anomalously resistive. However, Lutsenko, et al[15,16], showed that the current disruption was not due to ion instabilities, but rather that a double layer was created in the plasma. The external voltage drop fell in the double layer so that the current was very low. Large amplitude waves were excited, and electrons were strongly heated on the high potential side of the double layer. It was shown[17] that the plasma waves were excited by an electron beam which is formed by the acceleration of the electrons on the low potential side of the double layer. These electrons form a beam on the high potential side. Lutsenko, et al[15], were able to produce a double layer by creating a density depression at one location in the plasma. They also observed that the cathode layer would sometimes leave the cathode and become a double layer.

Experiments[18] and particle simulation calculations[5] have shown that double layers are excited if the electron drift velocity is larger than the electron thermal velocity, i.e., $V_d \gtrsim v_e$. In addition, we[5] have shown that double layers formed at locations of density depressions, and that the electron-to-ion temperature ratio must be large, i.e., $T_e >> T_i$, or the double layer will not form.

Thus, we come to the conclusion that double layers often form in current-carrying plasmas. Why are double layers important? First, they can be used to heat the plasma. Notice that in linear systems, an external voltage from anode to cathode is almost entirely shielded out of the plasma. But in this kind of system, double layers have been observed to form in the plasma. The external voltage drop falls in the double layer. Thus, electron and ion beams are formed which are injected into the high and low potential parts of the plasma, respectively. These beams excite two stream instabilities and heat the plasma. The electron heating has been observed, but the ion heating has not been measured. The second reason why double layers are important is that they might be used to produce extremely intense electron beams. Consider a z-pinch with densities in the range of $\gtrsim 10^{18}$, cm^{-3}. If potentials on the order of 1 MV are suddenly placed across the plasma, and a double layer forms near a hollow anode, an electron beam with currents on the order of 10^7 amps would be formed. The power output could be on the order of 10^{14} watts. Thus, double layers have very interesting applications.

The critical questions are: What is the mechanism which creates double layers? How do we control the location where double layers are formed? Will they be formed at very high voltage and current?

B. Results

We have begun measurements[19] with a device to answer the critical questions. In this device a magnetically confined, highly ionized plasma ($n \simeq 10^{12}$, cm^{-3}, $T_e \simeq 5eV$) is created in a glass vacuum chamber (plasma diameter = 7.5 cm and plasma wavelength = 35 cm). The plasma is created by a low energy electron beam. We find that when a voltage, $V \gtrsim 3kV$ is applied between the anode and cathode that a double layer is created in the plasma at the location of a plasma density depression. The double layer moves toward the cathode at a velocity of roughly the ion acoustic speed as seen in particle simulation calculations. The plasma is strongly heated by the double layer ($T_e \gtrsim 200eV$). High frequency electric fields are observed in the plasma with frequencies less than the ion plasma frequency, indicating that anomalous dc resistivity plays a role in the heating process.

IV. X-RAY PRODUCTION FROM A VERY HIGH POWER Z-PINCH

A. Introduction

We have used very fast vacuum sparks to produce soft x-rays ($\gtrsim$ 15eV) which we used to photoionize argon and produce highly ionized plasmas[20]. A vacuum spark is a z-pinch in which the plasma is made up of the anode and cathode materials. The system is pumped down to a low pressure ($P \lesssim 1\mu$). A charged capacitor bank is connected through a very low inductance transmission line to the anode and the cathode. A small capacitor is discharged near the cathode to supply a high density plasma which initiates the spark. We constructed a small system ($V = 10$ kV, $I_{max} \simeq 100$ kA) to test the high density limit of such devices. We found the amazing result that about 50% of the energy stored in the capacitor was converted into photons which ionized the argon gas. At a pressure of 10μ in argon the fractional ionization was 30% one foot from the spark. We found that essentially all the ionizing photons were created in the first quarter cycle of the discharge.

Several experimental[21,22,23,24,25,26] and theoretical[27] studies of the vacuum spark are reported. The discharge parameters are about the same in all the experiments, e.g., $V \simeq 10$ to 20 kV and $I_{max} \lesssim 250$ kA. The universal feature of the experimental work is that during the first quarter of the discharge, one or several minute (diameter less than 50μ) point plasmas are created in the discharge with electron temperatures and densities of $\lesssim 15$ keV and 5×10^{20} cm^{-3} (Ref. 24). These short-lived point plasmas emit short bursts (~ 10 nsec) of intense x-rays which consist of continuum as well as line radiation arising from highly ionized atoms (Turechek[21] identified radiation from hydrogen-like molybdenum). Turechek measured the time dependent spectra from the near infrared to hard x-rays. He found that throughout the soft x-ray to hard x-ray regime, the radiation was emitted principally when the point plasmas are created. Another universal feature is that at the same time the spark emits the x-rays, the spark current undergoes extremely sharp current dips ($dI/dt \simeq 10^{13}$ amps/sec!) and subsequent current bursts. The reason for the creation of these minute plasmas is not understood. However, it is generally believed that some as yet unidentified effect disrupts the current which forms a gap in the plasma. The rapidly changing current generates an enormous displacement electric field which accelerates ions and electrons across the gap to energies many times the capacitor voltage[24]. The electron and ion two stream instabilities of these very dense ($n_B \simeq 10^{19}$ cm^{-3}) beams result in the extremely rapid plasma heating and the resultant x-ray production. Cilliers, et al[24], have observed the electron beam which is created in the vacuum spark.

Recently, a set of measurements[15], discussed in the last section, were reported on a low density ($n \simeq 10^{12}$ to 10^{13} cm^{-3}) plasma which could shed some light on the phenomena involved in the vacuum spark. These measurements were performed in a long (60 cm) magnetically confined, fully ionized plasma. A 20 kV capacitor was suddenly switched across the system. The current began to flow as expected, but immediately, the current was disrupted. The current remained low for a long time ($\simeq$ 10 μsec), and then the current flowed again. Measurements of the plasma potential indicate a double layer propagating across the system during the current pauses. The external potential fell across this layer. An extremely dense electron beam was injected into the plasma on the high potential side of the layer, and the resultant two-stream instability caused very intense plasma heating. Finally, the double layer disappeared from the plasma, and the current then assumed a sinusoidal form, limited by the system inductance and capacitance. The most important feature of these results is that the double layer would form at a location in the plasma where the plasma was inhomogeneous. This suggests that the point plasmas seen in vacuum sparks could be the result of the interaction of a propagating double layer formed at the anode with the background plasma. Lee[21] has noted that the minute plasmas are formed at the tip of a very dense plasma which is traveling from the anode to the cathode.

Recently, Shiloh[25] has reported on a series of experiments with a very flexible geometry z-pinch. The system could be run as a vacuum spark or a hollow cylinder of gas was puffed into the anode-cathode gap. Measurements of x-rays ($\lesssim$ 1 keV) indicated that the hollow gas puff was far superior to the vacuum spark.

B. Results

We constructed a very high power ($V \leq 40$ kV, $I \leq 3 \times 10^6$ amp) vacuum spark. We have run the system with voltages up to 10 kV ($I \lesssim 7 \times 10^5$ amp). We find a very high conversion efficiency to soft x-rays ($\lesssim 50\%$) just as in the smaller systems we have constructed. The soft x-ray pulse ($E \lesssim 30$ eV) had a pulse width of about 3 μsec, close to the width of the current pulse. This implies soft x-ray intensities up to 3 GW. The yield of hard x-rays was not measurable. These generally negative results led us to design a very high power gas puff experiment. Shiloh's results[25] indicate that the yield of hard x-rays (≤ 1 keV) increased very rapidly with voltage ($\sim V^5$). Thus, our system is designed to operate up to 100 kV (as opposed to 30 kV for Shiloh's system).

V. PUBLICATIONS

A. Ph.D. Dissertations

1. H. M. Sze, "Experimental Investigation of Moderate Energy Electron Beam-Plasma Interaction and Thermal Electron Heating with Finite Amplitude Ion Density Fluctuations", UCD PRG R-24, June, 1977.
2. W. M. Bollen, " Experimental Investigation of Plasma Turbulence Driven by a High Density, Low Energy Electron Beam in a Double Plasma Device", UCD PRG R-39, June, 1979.

B. Abstracts of Oral and Poster Presentations

1. K. Mizuno and J. S. DeGroot, "Anomalous Absorption of Normally Incident Microwaves on Inhomogeneous Plasma", Talk given at the Seventh Annual Conference on Anomalous Absorptic of Intense High Frequency Waves, Ann Arbor, Michigan, May 18-20, 1977.

2. M. Bollen and J. S. DeGroot, "Measurements of Anomalous DC Resistivity", Talk presented at the 19th Annual Meeting of the Division of Plasma Physics, APS; Abstract in B.A.P.S. 22, 1160 (1977).

3. M. Bollen and J. S. DeGroot, "Measurements and Calculations of DC Resistivity in a Plasma", Talk presented at the 20th Annual Meeting of the Division of Plasma Physics, APS; Abstract in B.A.P.S. 23, 752 (1978).

4. E. W. Y. Ng and J. S. DeGroot, "Experimental Investigation of the Formation and Propagation of Double Layers", Poster presented at the 20th Annual Meeting of the Division of Plasma Physics, APS; Abstract in B.A.P.S. 23, 845 (1978).

5. W. M. Bollen, J. S. DeGroot, K. Mizuno, R. B. Spielman, and R. L. Walraven, "Experimental Investigation of Current Driven Ion Acoustic Turbulence", Poster presented at the 21st Annual Meeting of the Division of Plasma Physics, APS; Abstract in B.A.P.S 24, 935 (1979).

6. E. W. Y. Ng and J. S. DeGroot, "Measurements of the Formation and Propagation of Double Layers", Poster presented at the 21st Annual Meeting of the Division of Plasma Physics, APS; Abstract in B.A.P.S. 24, 960 (1979).

7. E. W. Y. Ng and J. S. DeGroot, "Measurements of Very Intense Double Layers", Poster presented at the 22nd Annual Meeting of the Division of Plasma Physics, APS; Abstract in B.A.P.S. 25, 916 (1980).

C. *Reports Published*

1. K. Mizuno and J. S. DeGroot, "Measurements of Finite Bandwidth Effects on a Parametric Instability", UCD PRG R-11, April, 1976; also in Phys. Rev. Lett. 39, 608 (1977).

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D. Report Planned for Publication

1. E. W. Y. Ng and J. S. DeGroot, "Double Layers and Anomalous DC Resistivity", UCD PRG R-58, 1981.

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